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Silvopastoral Practices

Livestock grazing, woodlots, and low-intensity forestry are traditional uses for nonarable lands throughout temperate North America. These opportunistic uses of otherwise low-income-producing lands occur across extensive areas of the western United States and western Canada, much of which is publicly owned. Private land holdings in the eastern and central portions of the United States often include woodlots, windbreaks, or nonindustrial forests that are grazed by livestock. Large blocks of grazed, privately owned industrial and nonindustrial forests are found in the southern and southeastern United States. Given the widespread co-occurrence of grazing and forestry across North America, it is understandable that the joint production of livestock and tree products is by far the most prevalent form of agroforestry found in the United States and Canada. Statistics for the exact size of area producing joint livestock and wood products are difficult to obtain because the usual categories of forest, rangeland, and pasture imply a dominant use. They do not adequately deal with multiple product systems such as forested rangelands, grazed forests, and pastures with trees. Forests currently occupy approximately 250 million ha of land in the United States and 436 million ha in Canada, of which only 70 and 60%, respectively, is commercial timber producing land (Lubowski et al., 2006; Brooks, 1993). Approximately 178 million ha of forest land in the 48 contiguous states of the United States are privately owned (Lubowski et al., 2006). Forestry and grazing are often competitive uses for lands that are economically unattractive for crop or orchard production. Forest and woodlands are common in all regions of the United States (Table 6–1), including highly agricultural regions such as the Corn Belt, Southern Plains, and Delta States. As with many indigenous agroforestry practices, grazing this land is commonly done because it just makes sense to farmers and ranchers. Considerable amounts of forage may be available for grazing under trees in mature open-canopied forest stands, such as the semiarid conifer forests (Fig. 6–1) and savannahs of the Northern Plains, Mountain, and Pacific States. Even closed-canopy forest sites may produce considerable amounts of grazable ground vegetation following timber harvest or natural stand opening events such as fire or wind fall. Grazing by ruminant livestock is an obvious way to control vegetation that competes with trees while making beneficial use of a vegetation resource that would otherwise remain unexploited. Approximately one-fifth of all forest land in the United States is grazed by livestock. This amounts to about 54 million ha (Lubowski et al., 2006), or 13% of the total land grazed in the United States (USDA, 1996). It exceeds pastures and grazed croplands, which provide approximately 53 and 25 million ha of grazing land, respectively.

North American Agroforestry: An Integrated Science and Practice, 2nd edition, H.E. Garrett (ed.)

Table 6–1. Area occupied by forest in different regions of the 48 contiguous United States (Lubowski et al., 2006).

Region	Federal forest	Private forest	Total forest
		10^3 ha	
Northeast	905	28,607	29,512
Lake States	3049	17,965	21,014
Corn Belt	1156	11,684	12,840
Northern Plains	535	1401	1,936
Appalachian	3174	27,002	30,176
Southeast	2496	8,330	30,826
Delta States	2195	18,510	20,705
Southern Plains	523	10,732	11,255
Mountain	39,977	16,502	56,479
Pacific	20,046	17,054	37,100
Total	74,056	177,787	251,843

In many regions, grazed forest lands occupy marginal sites for agriculture or plantation forestry. In other regions, grazing occurs as a secondary use of lands whose primary purpose is for high-yield timber production. In both cases, grazing and forage management intensity tends to be low. Grazing of native vegetation by cattle is by far the most common form of forest grazing in North America. Although fencing, watering systems, and burning can be used to enhance grazing potential, forested range grazing remains an extensive approach to forage resource use and often lacks the planned interactions between trees, forage, and animals required to be true agroforestry. Silvopastoralism is an agroforestry practice that intentionally integrates trees, forage crops, and livestock into a structural system of mutually supportive planned interactions. These interactions are managed intensively to simultaneously produce wood products, high quality forage, livestock, and environmental benefits on a sustainable basis. The forage component may be either native plants or introduced forage plants. The combination of trees and intensively managed improved pastures is a specific form of silvopastoralism called *silvopastures.* The more interactive approach to land use inherent in silvopastoralism provides a foundation for integrated commercial timber and livestock production systems. Both range and forest lands are increasingly being managed as integrated ecosystems that produce both saleable commodities, such as wood products, livestock, and hunting fees, as well as environmental services. Silvopastoralism reflects this ecosystem view. Environmental issues such as biodiversity, wildlife habitat, soil stabilization, watershed characteristics, pollution abatement, carbon sequestration, and scenic beauty are becoming increasingly important design elements of silvopastoral systems.

The most commonly practiced forms of silvopastoralism in North America are integrated forest grazing and silvopastures. Integrated forest grazing occurs when livestock are used to harvest native forest plants as part of planned forest ecosystem management. Although often extensive rather than intensive management systems, they are carefully planned to use livestock as a tool to manage forest trees and their understory plant communities for multiple outputs such as timber, forage, wildlife habitat, wildfire fuel reduction, and water quantity and quality. Silvopasture is the most intensive form of silvopastoralism. Trees and livestock are combined with improved pasture plants to form a carefully designed system that is an integration of intensive animal husbandry, silviculture, and forage agronomy practices (Fig. 6–2). While typically more complex than integrated forest grazing to design and to manage, silvopastures are highly productive. Skillful selection of forage plants and manipulation of microenvironment within silvopastures can extend the high quality green feed period for livestock, while providing them with shelter during inclement weather. When thoughtfully combined with pastures, native grazing lands, or crop aftermath, into an overall livestock production system, silvopastures may compete economically for sites currently used for some high value field crops.

Fig. 6–1. Grazed open canopied ponderosa pine forest, eastern Oregon.

Silvopastoral Concepts

Four basic principles characterize successful agroforestry systems: they must be *biologically possible, ecologically sustainable, socially acceptable,* and *economically feasible.*

Silvopastoral Biology and Ecology

The geographic range occupied by an organism is the result of its biological and its ecological amplitudes. Biological amplitude refers to the environmental requirements of individual plants and animals. In contrast, ecological amplitude refers to the requirements of plants and animals as they interact with other organisms within communities. Silvopastoral design must respect the biological limitations of each component while selecting and managing components for the desired interactions. There is little point in promoting land use systems that do not meet the site requirements of the individual plant and animal components or which fail to integrate components into a properly functioning community. Placing plants offsite, such as walnut trees on thin, poorly drained soils or clovers (*Trifolium* spp.) on basic soils is unlikely to be worthwhile. Likewise, combining fast growing trees with shade intolerant slower growing trees, or goats with young, highly palatable hardwood trees, will present considerable problems to managers.

In considering the amplitude of trees and other long-lived plants, it is important to recognize that they will be growing in the same location for a long period of time. Their general health will reflect average conditions. However, they will most certainly also encounter unusual periods of weather, outbreaks of disease, and infestations of insects or other damaging organisms that may prove fatal. Even apparently healthy conifer trees may cavitate (the water column breaks) and die very quickly in unusually hot and dry or cold and dry weather (Sharrow, 2004). For instance, approximately 10% of a plantation of 8-yr-old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] trees near Corvallis, OR died during a single atypically hot afternoon. The extreme as well as average site conditions will ultimately determine the success of plants in silvopastures.

Individual cohabitating organisms may help (facilitate) or may hinder (interfere) each other (Sharrow, 2008a). Interactions between individuals simultaneously include both facilitation and interference. What we observe is the net effect of these two processes. To the extent that facilitation exceeds interference, we observe organisms benefiting each other. When interference exceeds facilitation, we see competition, predation, and other negative consequences. Plants may interfere with each other by direct competition for site resources such as soil moisture and soil nutrients, or indirectly by improving habitat for diseases, herbivores, or other damaging organisms. Likewise, animals may compete for access to food, shelter, and other site resources. Animals and plants may also help each other. Hunter and Aarssen (1988) list nine ways in which plants have been observed to facilitate each other's growth by modifying the physical and biotic environment, including: providing physical support, microclimate modification, soil nutrient and structure changes, direct transfer of resources between interconnected plants, group defense against predators, supporting a favorable soil microbe community, attracting pollinators, and attracting seed dispersal agents. Animals participate in many similar positive interactions. Animals may gather together to protect each other from inclement weather or for group protection from predators. Herds provide social opportunities for sharing knowledge and responsibilities for child rearing. Mixed species herds allows for group defense while different grazing habits of the individual species supports efficient forage use and reduces potential for plants that are unpalatable to one grazer gaining a competitive

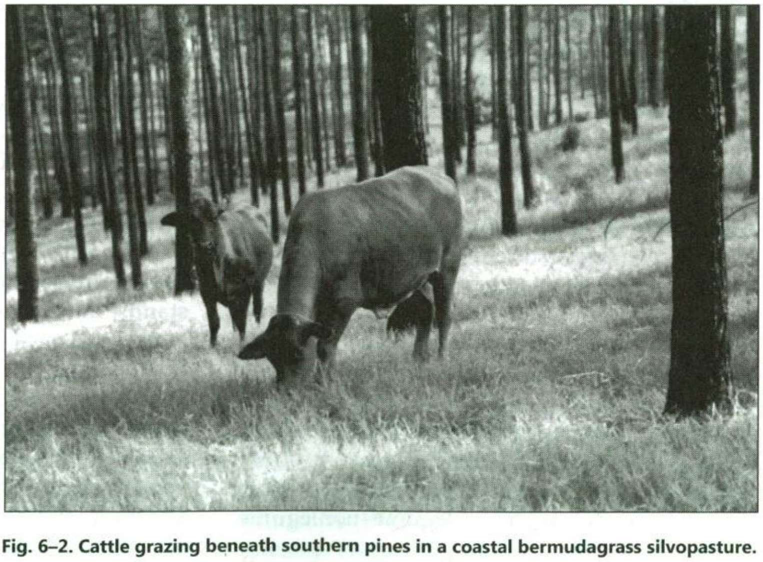

Fig. 6–2. Cattle grazing beneath southern pines in a coastal bermudagrass silvopasture.

advantage over more preferred forages. The challenge of silvopastoral system management is to successfully balance interference with facilitation to meet the needs of individuals as well as to provide a framework within which plants and animals can successfully interact to form a productive community.

Silvopastoralism influences ecosystem processes of hydrology, nutrient cycling, energy flow, and succession primarily through manipulation of community structure. The basic strategy is to combine forest, pasture, and livestock in such a way that each component produces usable products (productive functions), contributes to stability and conservation of land resources (environmental functions), and directly facilitates production of other components (service functions). Both tree and livestock production may be enhanced because trees provide shelter for livestock and pasture plants, while livestock serve to control weeds, to recycle nutrients through their feces and urine, and to reduce escape cover for rodents that gnaw on trees. Service functions are often obtained at little cost as a result of production. For example, sheep control tansy ragwort (*Senecio jacobaea* L.), a toxic weed, while eating it as food (Sharrow and Mosher, 1982). Nitrogen fixation by plants such as subclover (*Trifolium subterraneum* L.), black locust trees (*Robinia pseudoacacia* L.), or red alder trees (*Alnus rubra* Bong.) increase soil nitrogen as a normal outcome of their growth while producing valuable forage or wood. Silvopastoral systems are often, therefore, low-input, sustainable systems that require little in the way of pesticide, or other off-farm inputs. It is the presence of these service functions together with efficient resource sharing among components in time and space that makes well-designed and managed silvopastoral systems more productive than are sets of monocultures of their individual components.

Less need for purchased inputs reduces dependency on outside supplies, reduces operating costs, and increases potential profit margins of tree and livestock products. The proper unit of reference for the biological or economic productivity of intercrops, such as silvopastoral systems, is the entire system rather than the individual component. The efficiency of intercrops may be expressed by the land equivalency ratio (LER) (Vandermeer, 1981), which is the combined area of crop monocultures required to produce the same total yield as one ha of intercrop. The LER of subclover–conifer silvopastures ranges from 1.18 to 1.6 (Sharrow et al., 1996). This compares favorably to that of other legume–nonlegume intercrops (Hiebsch and McCollum, 1987). In the Willamette Valley, near Corvallis, it would take approximately 1.6 ha (0.96 ha of forest plus 0.64 ha of pasture) to equal the total aboveground productivity of one ha of silvopasture on a moderately productive commercial timber site (Sharrow et al., 1996). This high biological productivity together with the large area suitable for silvopasture makes it a strong potential agent for carbon sequestration to help check global climate change (Montagnini and Nair, 2004). Although most carbon offset programs have focused on forests' ability to store carbon in wood, soil rather than vegetation is where most terrestrial carbon is stored. Grasslands may accrete as much carbon as forests (Corre et al., 2000), but their contribution is often overlooked because it is predominately stored underground in soil organic matter (de Groot, 1990). Silvopastures may outperform either pastures or forests as carbon sinks because they store carbon using both forest (wood) and grassland (soil organics) mechanisms. Sharrow and Ismail (2004) estimated that cool-season pasture–Douglas-fir silvopasture in western Oregon accumulated approximately 740 kg ha^{-1} yr^{-1} more carbon than forest, and 520 kg ha^{-1} yr^{-1} more carbon than pastures during its first 11 yr after planting. Potential carbon storage in U.S. silvopastures is substantial, estimated by Montagnini and Nair (2004) to be at least 9 Tg yr^{-1}. Landowners would be encouraged to adopt silvopasture for environmental benefits if they could capture some of their financial value. Shrestha and Alavalapati (2004) estimated that Florida households may be willing to pay $30 to $71 yr^{-1}, either directly or indirectly through subsidies, for environmental services from silvopastures. Cashing in this value has been difficult to achieve in practice. While carbon credits are traded in the U.S., their value is inconsistent and varies wildly with public pressure on polluters and pollution regulations. Assuming that temperate silvopastures will sequester about 1 ton C ha^{-1} yr^{-1}, this environmental service would have sold for about $3 on the Chicago Climate exchange in 2006.

Silvopastoral systems may be established following harvesting or thinning of existing tree stands, under open-canopied forests and woodlands, or in pastures and other agricultural lands. In all cases, a succession-like process will begin, based on existing vegetation and seeds present in the soil seed bank (Sharrow, 2008b). Desired trees and forage plants are often planted to direct succession toward a desired plant community. The initial succession process tends to favor existing established plants over establishing plants.

Therefore, planting tree seedlings into an existing stand of perennial forage plants is generally less successful than planting trees and pasture plants at the same time so that they can establish together. Conceptually, there are three potential management periods in the life of a silvopastoral system: tree establishment, open-canopied forest, and closed canopy forest. Management during the tree establishment phase follows normal pasture management practices with additional focus on establishment and growth of trees. Particular attention is paid to competition from resident forage plants or tree damage by native and domestic animals. Trees have relatively little direct impact on forage plants or livestock production during the establishment phase. The open-canopied forest phase is the most interesting to agroforesters because during this period, competition and facilitation between trees, livestock, and pastures affects the productivity of each component. Because both pastures and tree production contribute significantly to land productivity, this is the period when LER is the greatest. The impacts of trees on understory forage production is now of special concern. If tree canopies are allowed to close, insufficient light reaches the ground to support forage for livestock grazing. Closed-canopy tree stands essentially cease to function as an agroforest and are managed as a late rotation forest. Many silvopastoral systems attempt to reduce or even prevent this phase by planting at low initial tree densities, thinning trees as soon as possible, and pruning off lower branches. The presence and duration of the three stages will vary with site productivity, management goals, and the stage within the succession process at which the system is initiated. In general, higher-producing sites will tend to move quickly toward forest canopy closure unless actions are taken to control tree dominance. On some low-producing sites, such as those with shallow soils or in low precipitation zones of the western United States, forests naturally remain open-canopied throughout their development.

Social Factors

The sociology and economics of silvopastoralism may be viewed at two scales, the societal regulatory scale, and the individual practitioner scale. Silvopastoral systems differ from agriculture, and even other forms of agroforestry in their natural appearance. Many silvopastoral systems are based on integration and management of naturally occurring combinations of native trees and understory plants. When exotic forages are planted under native tree species, the resulting forests often have a similar visual structure as grazed native vegetation. Most silvopastoral systems, therefore, come under social pressures that are more similar to native forest or range lands than they are to agricultural lands. This is important because people often judge their relative stake in land management based on their assumption of individual versus societal ownership. Human-created things (such as agriculture) have individual owners, while natural things (forest or range land) are more likely to be viewed as part of our natural heritage. For instance, forest land is often zoned in a separate category from agricultural land for taxation and regulatory purposes. While regulation of agriculture is mostly concerned with environmental pollution, soil erosion, and other offsite effects, regulation of forest practices are additionally aimed at maintaining the integrity of forest and woodland ecosystems. This places additional restrictions on silvopastures than would be required of pastures or other agricultural lands. Requirements for unimpacted "set back" zones along streams are often wider for forest than for agricultural lands. Agricultural and forest chemicals are labeled separately, so a herbicide that is acceptable for use on agricultural lands may be illegal if applied to control the same weed on forest lands. Forest and agricultural lands may also have different tax systems. For example, agricultural lands are often assessed a yearly tax based on the value of the land. Forest lands are often assessed a small yearly fire protection fee, and the main tax is paid as a "severance tax" when timber is cut and sold. Before converting pasture or agriculture lands to silvopastures, one should check with local regulators to understand zoning and tax issues.

Societal desires for forest management are transmitted to land managers through economic and political means (Koch and Kennedy, 1991). Recently, these two forces have come into conflict as limited world timber supplies have supported high stumpage prices at a time when public policy is promoting sustainable multiple-use management of public and private forest lands through laws and other regulations that effectively reduce wood harvest. Economic incentives for afforestation are currently available through federal or state conservation reserve, wildlife habitat enhancement, or other reforestation programs. Within this regulatory environment, environmentally based multi-product systems such as silvopastoral systems have an advantage over plantation forestry. Social acceptability of silvopastoral systems may be increased by applying Brunson's (1993) principles of socially acceptable forestry. The principles that natural-like systems are more acceptable, that the perceived intent of management actions is as important as the actions taken, and that all actions are judged relative to perceived alternatives are particularly relevant to silvopasture design. The intent to maintain natural processes within a healthy and productive ecosystem makes silvopastoralism potentially more socially acceptable than the alternatives of agricultural pastures or plantation forestry.

As suburban growth encroaches on forests, and people become increasingly environmentally sensitive, the visual appearance of forest "view sheds" is becoming a consideration in forest management practices. Forests and woodlands that were once quite remote are coming into full view of the public who are expressing definite opinions about the appropriateness of forest and woodland management. Likewise, small yet vocal local groups are beginning to discuss the desirability of preserving the visual "agricultural landscape" through the land use zoning process. In California, for example, land owners can get tax deferrals and even cash payments for surrendering the right to convert their rural land to suburban uses such as housing development. Silvopastoral systems generally are visually acceptable within rural landscapes. Integrated forest grazing systems often have a normal forest structure and an open grassy understory similar to early succession plant communities of native forests. The neat rows of pruned trees in silvopastures with a well-groomed pasture understory are open and park-like. Although adjacent landowners generally value these "green spaces", there have been complaints of trees blocking views and of forest wildlife, such as deer, damaging gardens.

Silvopastoral technology will only be adopted by practitioners if they perceive the benefits to outweigh the costs. Natural resource decisions often reflect both tangible benefits and intangible amenity values. Although income considerations are an important factor in natural resource management (Zinkhan and Mercer, 1997), the importance of amenity values should not be underestimated. Income implications can be readily evaluated by examining expected cash flows, internal rates of return on investment, and net present value (Sharrow, 2008c). The intangible nature of amenity values such as beauty, fairness, desire to be a responsible neighbor, or leaving the land in good condition for the next generation are often overlooked because they are very difficult to quantify. They do influence individual decision makers, however. Landowners often recognize these noncash benefits and adjust their decisions to favor them. In a survey of southeastern U.S. landowners (Workman et al., 2003), over 70% of responses ranked aesthetics, wildlife habitat, soil conservation, biodiversity, and water quality as highly important benefits of agroforestry. In Washington State, 77% of the nonindustrial forest owners surveyed (Lawrence et al., 1992) listed "aesthetically pleasing" and 66% listed "increased biodiversity" as advantages of agroforestry. The two most frequently given reasons for owning land were to pass it on to children (80% of respondents) and to keep it natural (75% of respondents). Likewise, nonindustrial forest land owners in Oregon (Elwood et al., 2003) ranked "good stewardship" and "leaving a legacy" above timber production, producing income, or grazing as main objectives of their land management.

Economic Factors

Integrating trees, forage crops, and livestock creates a system that produces a constant flow of marketable products while maintaining long-term productivity. Cash flow is especially important for land holders who must support themselves while pasture or crop land is being afforested. Economic timber rotations for conifers can be quite long, ranging from 20 yr in southern pine forests to 65 yr for coastal Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] in the Pacific Northwest. This places final timber harvest outside of the economic lifetime of many middle-aged land holders. Intensive silvopastoral practices, such as grazing, and fertilizing increase tree growth, so less time is required to produce high-value timber products such as saw timber, and veneer logs. Early timber harvest speeds up cash flow and puts investments at risk for a shorter period. Economic risks are reduced because livestock and forest components require different inputs, share few common diseases and pests, and sell into different markets (Sharrow, 2008d). Risks can be further reduced by using tree and livestock components that have previously been successfully produced on similar sites and for which local markets and production infrastructure already exist. Sharing costs between livestock and timber components reduces individual component production costs and enhances their marketing flexibility. Thus, silvopastoralism is often more profitable and less risky than either forest or livestock enterprises alone.

Long-term investments such as timber stands are very sensitive to the time value of money. Money made or saved now is much more valuable than money later. This is because money invested in trees must compete with other potential investments. This "opportunity cost" accumulates each year much as a compound interest rate in a bank account does. So, $1 invested in a timber stand now, requires almost $24 of income at the end of a 65-yr rotation to equal being put in the bank at 5% annual interest. This cost becomes even larger when one considers the possibility of money losing value over time (inflation). The buying power of our initial investment dollar was 100 cents. However, 65 yr later, 3% annual inflation would reduce its buying power to only about 8 cents. Both opportunity cost and inflation eroding the value of income can be lessened by reducing the initial investment and by emphasizing early income that can either be used to pay off the investment or to cover current expenses. Agroforestry can reduce investment costs by substituting service functions such as animal grazing and weed control for purchased inputs such as herbicides. Livestock also generate income during the initial years of the timber rotation. This makes agroforestry very economically efficient compared to forest plantations. For example, a landowner in western Oregon converted an existing unmanaged mixed Douglas-fir and hardwood stand into a conifer–sheep silvopasture. Combined income from the salvage value of the previous trees together with the income from livestock sales paid off the entire investment within the first 8 yr of the 60-yr rotation. He is now producing income each year as his trees grow on toward the big pay off at final harvest. Although the amount of money saved or income generated during the early years of a timber rotation may seem small compared to the large amount of income when the final timber crop is sold, it has a huge effect on the profitability of the timber investment.

According to surveys of U.S. public land-use professionals in the Pacific Northwest (Lawrence and Hardesty, 1992) and the South (Zinkhan, 1996), increased economic diversity and higher total monetary returns were perceived as the primary tangible benefits of silvopastoral practices. In Washington State, 74% of private nonindustrial forest managers surveyed listed increased income as an advantage of agroforestry. Research supports these perceptions. In a simulated loblolly (*Pinus taeda* L.) pine–forage–beef cattle system for the Southern U. S. Coastal Plain, silvopasture net present value per unit area was 70% greater than a pure forestry operation (Dangerfield and Harwell, 1990). In Louisiana, a coastal bermudagrass [*Cynodon dactylon* L. Pers.]–loblolly pine agroforest produced 234 kg ha^{-1} $year^{1}$ of meat and 3.3 m^3 ha^{-1} yr^{-1} of wood (Clason, 1995). Although establishment costs were $716 ha^{-1}, the internal rate of return for this silvopastoral system was 13%, which exceeded timber management and open pasture options by 4 and 7%, respectively. In western Oregon, KMX hybrid pine (*Pinus attenuata* Lemm. × *Pinus radiata* D. Don) silvopasture grazed with sheep is projected to yield a 22% internal rate of return after 22 yr (Sharrow and Fletcher, 1995). These results can be attributed to comprehensive land utilization obtained by combining timber and livestock production; a reduction in time between cash flows, by selling livestock; and synergies such as trees utilizing applied fertilizer and livestock manure. In addition, trees can have a climate-stabilizing effect on the livestock, resulting in less energy consumption and lower mortality (Wilson et al., undated).

Most silvopastures are designed to maximize forage production with as little negative impact on trees as possible. The relatively high value of mature trees generally makes them a focus of planning. Having a full stand of trees at rotation age is generally assumed to be a goal. This emphasis on trees leads one inexorably toward taungya-type systems in which agriculture is only the initial stage leading to a closed-canopy forest. Adoption of silvopasture technology has been more rapid by farmers and ranchers, seeking to afforest agricultural lands or to manage nonindustrial forest lands, than by silviculturists considering reforestation options for commercial forests. This may to some extent reflect the availability of investment capital following timber harvest. Reforestation of harvested lands can be financed from proceeds of timber sales. The opportunity cost of this money is often lower than the interest paid on loans taken out by farmers or ranchers seeking to afforest pastures or crop lands. Where forest practice regulations require replanting trees, reforestation may be considered a cost of harvest that is not carried forward as a cost of the next generation of trees. This greatly improves cash flow, increases the internal rate of return and net present value of the timber investment, and reduces the economic pressure for immediate income. Need for an income stream to support the costs of afforestation, on the other hand, encourages ranchers to continue to graze their lands. Nonindustrial forest managers tend to be balanced resource managers who value aesthetics and land conservation as well as income generation (Lawrence et al., 1992), making them natural clients for agroforestry. This is especially true for the urban fringe hill lands where owners have other sources of cash income. This suggests that largely untapped clienteles may exist for agroforestry systems that emphasize forage production, environmental services, and intangible benefits such as aesthetics and independence through production of household subsistence needs. Clearly, successful integration of livestock, forages, and trees requires knowledge and managerial effort greater than managing any commodity separately. However, most agricultural and silvicultural information is specific to the technological context from which it came. The biological information necessary to produce hybrid systems is just now being acquired. Silvopastures offer substantial rewards to knowledgeable managers. They are probably a poor choice for absentee landlords or others who desire a low level of management input.

Integrating Silvopastoral Components

Silvopastoralism is one of the most complex forms of agroforestry. While alley cropping or forest farming combine two components, trees and crops, silvopastoralism deliberately integrates three components, trees, ground vegetation and domestic livestock. The many possible combinations of trees, livestock, and forage plants for a specific site provide a wide array of options to meet many different management goals. Considerations should be given to potential markets, to soil and climatic conditions, and to crop management compatibility when making tree, livestock, and forage crop selections.

Most silvopastoral systems are designed to enhance long-term value of the timber component, while sustaining short-term cash flow value of the livestock component. The timber component should consist of marketable, high-quality, fast-growing, deep-rooted trees. Coniferous trees are somewhat better suited for silvopastures than hardwood trees because they adapt to a variety of growing sites, respond rapidly to intensive management, have conical crowns that permit more light to reach the forest floor and are less likely to be browsed by livestock. Native vegetation may be retained as the forage base. When choosing improved forage species for use in silvopastures, preference is given for plants that are nutritious, palatable to livestock, shade and drought tolerant, responsive to intensive management, share site resources well with trees, and tolerate grazing.

Resource sharing in time and space is a fundamental concept in selecting tree and forage components. Evergreens, such as conifer trees, are able to grow anytime environmental conditions permit. Most forage plants, on the other hand, are seasonally dormant. This makes it possible to select forages that concentrate their growing cycle in the rainy season, leaving all soil moisture in the dry season to support tree growth. Subclover, for example, is used because it is a cool-season annual that grows quickly in the spring, then dies. When combined with Douglas-fir in the maritime zone of the Pacific Northwest, it completes most of its yearly growth before spring rains end. The trees continue to grow until winter, using stored soil moisture and summer-fall rains. Subclover also restricts its root system to the top 15 cm of soil, leaving the soil moisture and nutrients below this shallow zone for other plants. Douglas-fir trees have deeper roots that are generally able to penetrate lower into the soil profile. Such resource partitioning in time and space provides design opportunities for selection of tree and forage plants whose combined root systems are able to capture all site resources without undue competition in the zones of overlap. Most soil nutrients are associated with the organic matter zone near the soil surface. Both pasture plants and trees require soil nutrients to support their growth. Therefore, even deeply rooted trees will have fine roots in the upper soil layers where they will compete with pasture plants for nutrients. In crop–tree agroforestry, plowing to prepare the land for cropping cuts off the shallow tree roots and controls root competition within the plow zone. This is not possible with perennial crops such as native grasslands or permanent pastures. Here, selection of tree and pasture plants that share soil resources well is critical to maintaining the health of both components.

Animal Component

Animals in silvopastoral systems are both a product and a management tool. Silvopastoral management considers both livestock production and manipulation of wildlife habitat to favor desired game animals. Sales of hunting rights and livestock products are a way of converting ground vegetation into income. At the same time, controlled livestock grazing provides an effective and inexpensive tool for vegetation manipulation. Wild animals also can be used to manipulate silvopastoral ecosystems, but their activities are harder to direct in a precise manner. Large ungulates such as deer and elk may damage trees by browsing or rubbing on young trees. They may also benefit trees by reducing brush or invading hardwood trees. In western Oregon, for example, choke cherry (*Prunus emarginata* Dougl.) readily invades fenced areas and dense brush patches that exclude deer. High deer populations even in suburban areas have so effectively controlled the plant that it is rarely seen outside of these refuges and few people recognize its invasive potential. It is useful to note that grazing affects both the top (shoot) and the bottom (root) of a plant. The plant is a balanced system with the root supplying water and nutrients to the top and shoot supplying food to the roots. When the top is pruned back by grazing, the plant reduces the depth and spread of the root system to restore this balance. Therefore, what happens to the top of a plant is mirrored underground. Grasses have extensive fibrous root systems that make them fierce competitors for soil moisture and nutrients in the upper soil layers. Grazing can control competition between young trees and forage plants by removing their leaf area before soil moisture depletion (Doescher et al., 1987). Prescription grazing, which applies the proper amount, distribution, and season of grazing, has proven helpful in controlling competition between trees and forage plants (Doescher et al., 1987; Sharrow, 1994). If grazing is done properly, silvopasture trees may display less summer moisture stress and have greater diameter growth than trees in nearby ungrazed forest stands (Carlson et al., 1994). In a trial near Corvallis, Oregon, Douglas-fir trees in a silvopasture grew 14% faster in diameter than did adjacent forest trees during their first 4 yr (Sharrow, 1995). Approximately half of the additional diameter growth increase occurred during the dry summer–fall period when plant moisture stress limits tree growth. Similar observations were reported (Gibson et al., 1994) for 14-yr old loblolly pines that were 34% greater in diameter in silvopastures than in forests. A higher percentage of late season wood in annual growth rings of silvopasture trees suggests that most of the increased growth occurred during the summer–fall period.

The amount and quality of forage available in the agroforest varies with tree occupancy and the type of trees and forage crops present. Trees in young agroforests withdraw relatively few site resources, and understory yields approximate those of similar pastures. As trees grow, their demand for onsite resources increases and forage production declines accordingly (Sibbald et al., 1994). For example, Douglas-fir in western Oregon had relatively little effect on agroforest forage production until trees were 9 yr old, then it declined rapidly to 54% of adjacent pasture yields when trees were 11 yr old (Sharrow, 1991). Trends in forage yields are reflected in livestock carrying capacity. Bond and Campbell (1951) recommended a stocking rate of 0.16 grazing units ha^{-1} for grazing native forage in young Louisiana pine plantations containing 200 trees ha^{-1}. Because forage yields decrease as trees grow, they suggested that the plantation be thinned to 140 tree ha^{-1} or to a basal area of 18.5 m^2 ha^{-1} before age 10. Subsequent management, including thinning to a basal area of 18.5 m^2 ha^{-1} at 5- to 7-yr intervals should support grazing at 0.1 grazing units ha^{-1}.

Potential tree damage due to browsing or trampling by livestock is often mentioned as a concern by potential agroforesters (Lawrence and Hardesty, 1992; Zinkhan, 1996). Trampling damage is largely confined to very young trees and is more common with cattle than it is with sheep or goats. Livestock generally do not actively feed on conifers when other palatable forage is present (Doescher et al., 1987; Sharrow, 1994). Although not particularly attractive to livestock, conifers foliage is most palatable when buds have just broken and the new growth is still light green in color (Sharrow, 1994). Animals do like variety in their diet and will eat a small amount of conifer foliage each day, especially when other sources of woody browse are not available. Goats tend to consume more browse than will cattle or sheep and are generally more difficult to safely graze among small trees. Once the animals have decided that alternate forage is either unavailable or unattractive, active feeding on trees can quickly impact young trees. For this reason, some agroforesters prefer to either cut hay or to protect trees with fencing or individual tree tubes until trees have grown above the reach of livestock (Sharrow and Fletcher, 1995). Although browsing by livestock can interfere with regeneration of hardwood stands, conifers are fairly tolerant of defoliation (Pearson and Cutshall, 1984) provided that the terminal bud remains intact (Sharrow et al., 1992; Sharrow, 1994). Young Douglas-fir, for instance, showed little reduction in either height or diameter growth following 50% defoliation in either spring or summer (Osman and Sharrow, 1993). Goats, horses, and to a lesser extent, sheep or cattle will sometimes strip bark from young trees. Bark stripping is more likely to occur on young hardwoods trees than it is on older trees that have developed a corky bark or on conifer trees because of their pitchy bark. Any break in the bark is undesirable because it provides opportunity for disease or insects to enter the tree. However, the direct effect of bark removal interfering with water and nutrient flow through the stem usually does not reduce tree growth unless over half of the circumference of the stem is debarked (Sharrow, 1994). Even when trees are temporarily damaged by grazing, the benefits of controlling competing vegetation may provide greater tree growth over time (Sharrow et al., 1992).

Forest managers often mention soil compaction by livestock as a possible problem in grazing forest lands. In the Southeastern pine zone, the combination of burning and moderate to heavy grazing increased bulk density, reduced pore space, and decreased percolation rates of the soil (Duvall and Linnartz, 1967). Bezkorowajnyi et al. (1993) also observed an increase in soil bulk density from cattle grazing. They found medium and high levels of soil compaction reduced water infiltration and nitrogen cycling, resulting in slower seedling growth. Boyer (1967) reported that light cattle grazing on a longleaf pine (*Pinus palustris* Mill.) site in southwest Alabama reduced survival rates by 23% and diameter growth rates by 13% over the first 5 yr of the regeneration period. Negative effects of grazing on trees, often referred to as "soil compaction", actually includes both soil compaction and direct physical damage by trampling on shallow tree roots. Shallow-rooted trees such as Douglas-fir or western red cedar are particularly sensitive to direct root damage if livestock hooves actually penetrate the soil. Although most grazing, equipment movement, or even human foot traffic will compact soils to a measurable extent, only severe compaction generally reduces plant growth. Severe soil compaction reduces water infiltration rate, soil aeration, and soil water holding capacity by collapsing both large and small soil pores. Lack of soil pore space to provide needed oxygen and water reduces plant growth. Not all soil compaction is undesirable, however. Mild to moderate compaction can benefit plants by increasing soil water holding capacity. During the early stages of compaction, large air-filled soil pores are collapsed down to form smaller pores that hold soil water. Unless larger pores are so infrequent that poor soil aeration results, moderate compaction can actually increase plant production by increasing soil water storage. Sharrow (2007) reported that 11 yr of sheep grazing reduced soil infiltration rate by reducing volume of large soil pores and increased the volume of small pores, thus increasing soil water storage. Production of both Douglas-fir trees and pasture plants was higher on these moderately compacted silvopasture soils than on the uncompacted forest plantation sites nearby. The compactness of a soil at any point in time is a balance of factors that compact soil and those that loosen it back up by forming new pore space. Physical uncompaction processes such as freezing–thawing or wetting–drying cycles and biological agents such as large and small burrowing organisms all are most active near the soil surface. This is significant because, unlike heavy machinery that compacts soil to great depth, livestock hooves generally only compact the top 2 to 4 cm of soil. Such damage can be easily reversed by natural processes. Sharrow (2007), for example, observed that the effects of 11 yr of sheep grazing on soil bulk density, total soil porosity, and air-filled pore space in the top 6 cm of soil in a silvopasture were erased by 2 yr of no grazing. It is unclear if high producing silvopastures are more or less subject to soil compaction than are the generally lower-producing grazed forest sites with native vegetation. The higher productivity of silvopastures should increase soil biological activity, while at the same time supporting more animal days of grazing with its associated greater foot traffic. Prescribed grazing management plans use water, salt, herding, and other tools to see that animals do not concentrate their use on small portions of the pasture. Proper animal distribution, together with avoiding grazing heavy (clay) soils when they are saturated with water, minimizes the chance of severe soil compaction.

Many native animals find the diverse structure of agroforests attractive. Large herbivores, such as deer and elk, may make extensive use of silvopastures as feeding areas. The relatively early green-up and high nutritional quality of grazed forests makes them a better source of food for large herbivores than many native forest plant communities (Rhodes and Sharrow, 1990). Perching birds such as thrushes often use trees as observation posts from which to hunt worms and insects in the open pasture areas between trees. Concentration of wildlife use can be a potential problem in small-sized plantations that draw animals from a large local area. Deer and elk may consume a considerable portion of the forage produced, browse young trees, and debark or break trees while rubbing the velvet from their antlers. The terminal leader of conifer trees may be broken off when heavy bodied birds such as robins attempt to perch. Young trees may be protected from animal browsing damage by chemical deterrents or physical barriers (Sharrow and Fletcher, 1995). However, the simplest solution is often to increase agroforest size so that animal use does not exceed tolerable levels.

Forage Component

In the southeastern and northwestern United States, cool-season (C_3) forages such as subterranean clover (*Trifolium subterraneum* L.), white clover (*Trifolium repens* L.), perennial ryegrass

(*Lolium perenne* L.), tall fescue [*Schedonorus phoenix* (Scop.) Holub], and orchardgrass (*Dactylis glomerata* L.) have been established as forage resources under forest canopies (Fribourg et al., 1989). Cool-season forage plants are especially valued in the southern United States because they provide winter and spring forage where native forages are mainly warm-season growers. Bermudagrass (*Cynodon dactylon* L.), dallisgrass (*Paspalum dilitatum* Poir.), and bahiagrass (*Paspalum notatum* Fluegge), as well as other warm-season (C_4) grasses, have been used in silvopastures in the southeastern states (Halls and Suman, 1954; Hughes et al., 1965; Lewis et al., 1983). Good results have been achieved with coastal bermudagrass in young southern pine agroforests (Clason, 1995). Bahiagrass, however, has proven to be the most successful in growing beneath older trees (Burton, 1973; Lewis et al., 1983). This ability is often described as "shade tolerance". Trees compete with forage plants for light, nutrients, and soil moisture. Competition for all of these needs increase as one approaches a tree. Water soluble nutrients such as nitrogen and potassium are often taken up by plants along with water. It is very difficult, therefore, to separate their effects on plant growth. Burner and Mackown (2006) and Burner and Belesky (2007) recently attempted to assess competition for nutrients, light, and soil moisture independently. Tall fescue [*Schedonorus phoenix* (Scop.) Holub] growing in the center of 2.5 m alleys between 8- to 9-yr old loblolly pines trees had N acquisition efficiency (kg N accumulated per kg of N added) that was half that of fescue growing in the open when N was applied at less than 200 kg N ha^{-1} (Burner and Mackown, 2006), possibly because of reduced light or from tree root competition for soil moisture in silvopastures. Burner and Belesky (2007) compared growth and physiology of tall fescue with and without irrigation in a later experiment at the same site. They concluded that differences in photosynthetic assimilation rate (PAR) had a greater effect on tall fescue growth than did soil moisture, implying that competition for light was a significant determinant of forage productivity when high canopy cover (approximately 70%) reduced understory light levels to less than 20% of that of open meadow. Silvopasture management often seeks to prevent understory light levels from declining below 50% of incident sunlight. In open canopy stands, competition between trees and forage plants may be as much for moisture and soil nutrients as it is for light (Sharrow, 1999). This suggests that drought tolerance may be as important as tolerance to low light levels when selecting an understory forage plant for mid-rotation silvopastures.

Legumes such as subclover or white clover are often included in silvopastures. They are a highly nutritious food for livestock and serve as the nitrogen source for the agroecosystem. *Rhizobium* bacteria live symbiotically in the roots of legumes. They derive their nutritional needs from the host plant and, in return, convert atmospheric nitrogen gas into water soluble forms that are available to the host. Clovers can "fix" considerable amounts of nitrogen. A healthy grass clover pasture can fix over 100 kg ha^{-1}yr^{-1} of atmospheric nitrogen (Heichel, 1983). This is the equivalent of over 200 kg ha^{-1}yr^{-1} of ammonium nitrate fertilizer. The legume–*Rhizobium* association is very specific with only a limited range of legumes, called the cross inoculation group, being effectively colonized by each *Rhizobium* species. To ensure that the needed *Rhizobium* is present, we generally inoculate legume seed or seedlings with appropriate live *Rhizobium* strains before planting. Nitrogen present in clovers is transferred to associated grasses and trees when leaves, stems, and roots senesce and decompose. Grazing greatly speeds up this process. Livestock retain relatively little of the nutrients that they consume. Most nutrients pass through them and are quickly returned to the soil as urine and feces. As explained earlier, grazed plants generally reduce roots to re-establish an efficient root–shoot ratio. The senesced roots that are shed decompose, releasing their nutrients back into the soil nutrient pool where they can be reused. Livestock grazing, therefore, provides both an important nutrient transfer mechanism, and a tool by which both aboveground and belowground organic matter dynamics may be managed.

Established trees are often strong competitors with ground vegetation for site resources. It is unrealistic to expect forage yields under established conifer trees to be as high as that of open pasture or rangeland. Tree size, density, and pattern all influence understory forage production. Typically, trees have little impact on understory forage production of cool-season (C_3) plants until their combined canopy cover exceeds 35% (Krueger, 1981). Cool-season plants using the C_3 photosynthetic pathway typically saturate with energy at about 50% of direct sunlight. Warm-season plants with the C_4 pathway, however, can use much higher levels of light. Therefore, while C_3 plants such as ryegrass, bluegrass, or orchardgrass grew as fast under 50% shade as they did in full sun, C_4 plants such as bermudagrass, big bluestem (*Andropogon greardii* Vitman), and switchgrass (*Panicum virgatum* L.) only produced 66 to 75% as much forage under 50% shade as they did in full sun (Lin et al., 2001). Once shade increased to 80%, all plants suffered, but the C_3 grasses still produced 68 to 81% of full sun yields while the C_4 grasses only produced 15 to 39% of full sun yields. Decreases in warm-season forage production have been reported when the tree canopy cover was less than 35% (Brauer et al., 2004). Annual forage yields of a mixture of bermudagrass (C_4) and tall fescue (C_3) growing under 6- to 8-yr old loblolly pines with measured tree canopies of 20 to 32% in central Arkansas were 50 to 60% less than that of open pasture. Decreases in warm-season forages including bermudagrass were greater than that observed for the tall fescue. Forage yields tend to drop off quickly as canopy cover and tree basal area increase beyond a critical threshold. For example, yields of Pensacola bahiagrass, coastal bermudagrass, and dallisgrass established in a 5-yr old slash pine (*Pinus elliottii* Engelm.) plantation (Hart et al., 1970) declined by over 80% as the canopy began to close 5 yr later. Data from Wolters et al. (1982) relating declining forage production to increasing stand basal area found a declining curvilinear function. However, Ares et al. (2003) found that forage production and livestock gains decreased in a linear fashion with increasing stand basal area. The critical threshold will vary with tree and forage species as well as with site characteristics. Deciduous hardwoods, such as oak (*Quercus* spp.), birch (*Betula* spp.), or chestnut [*Castanea dentata* (Marsh) Borkh.], reduce forage production less than do evergreen pines or Douglas-fir (Rozados-Lorenzo et al., 2007). Canopy leaf area and geometry is also important in limiting understory plant access to light and nutrients. The dense canopy of trees such as Douglas-fir and its tendency to retain multiple layers of branches near the ground make it a strong competitor with ground vegetation. Pines, in contrast, tend to have more open canopies with fewer but bigger branches that project upward and that cast less shadow. Experience in Oregon silvopastures is that KMX pines and ponderosa pines (*Pinus ponderosa* Dougl. Ex. Loud.) allow more light to reach the ground and grow more forage in their understory than do Douglas-fir. Similar experiences were reported for 4- to 6-yr old silvopastures in Spain where *Pinus pinaster* and *Pinus radiata* did not reduce pasture production as severely as did Douglas-fir (Rozados-Lorenzo et al., 2007). Pruning the bottom branches from Douglas-fir can dramatically increase pasture production by allowing light to reach under the canopy as the sun angle changes across the day.

Tree Component

Because forage yields decrease as tree canopies close, altering canopy closure patterns by reducing planting densities of conifers and changing their spatial arrangement can substantially increase forage production in mid- to late-rotation agroforests. Planting fewer trees and aggregating trees into rows or clusters also facilitates agricultural operations (Sharrow, 1991). Trees can be planted in single widely spaced rows ranging between 4.9 and 9.4 m apart, in strips of double or triple rows with wider spacing between strips of trees or in clusters. Cluster plantings may favor tree growth by quickly forming a forest microclimate within the cluster and by trees protecting each other from wind damage. However, clusters make fertilization, spraying, mowing, or other mechanical operations inefficient as a second pass perpendicular to the original application must be made to treat the area between the clusters. Planting trees in rows facilitates agricultural operations while greatly reducing tree impact on forage production with little immediate effect on tree growth (Sharrow, 1991). Sharrow et al. (1996) reported similar height and diameter growth of 8-yr old Douglas-fir silvopasture trees planted 2.5 m apart in a rectangular grid as those planted in clusters of 5 trees each with 7.5 m between clusters.

In general, trees planted in single or double rows grow as fast as those planted at the same density (trees ha^{-1}) in conventional square grids until their canopies begin to overlap, provided each tree has at least one side in full sun. It should be noted that stand density is averaged over the entire area planted. When trees are planted in single rows or in multiple row sets, the density within the row or set will be higher than the average stand density. This can decrease tree performance within sets of rows unless pruning or early thinning is used to reduce intraspecific competition. Multiple row configurations such as 3- or 4-row sets separated by wide alleys reduce performance of trees within the center rows once the tree canopies begin to coalesce. Lewis et al. (1985) reported that growth of slash and loblolly pine planted in double row strips with 5.5 m spacing between strips was similar to a conventional 1.8×3.6 m planting. At age 13, mean height and diameter for the respective plantings were 10 and 9.5 m and 117 and 112 mm. Similar results have been reported for slash pines growing in central Florida (Ares et al., 2005). In young timber stands, interspecific competition between trees and ground vegetation is much more pronounced than is intraspecific competition with other trees. Neither tree density nor planting pattern affect tree growth until the trees' spheres of influence begin to touch. As one might expect, special pattern and density become more important as trees grow. At an initial tree density of 1135 tree ha^{-1}, the basal area of 13-yr old trees averaged 12 m^2 ha^{-1} in both single and double row configurations with alley widths of either 7.3 or 12 to 14 m (Ares et al., 2005). Trees in both single and double row plantings with similar alley widths were approximately the same size at age 18. However, increasing the within-row density of either single- or double-row plantings to increase alley width (from 7.3 m to 14.6 m in single row or from 7.3 to 12.2 m in double-row plantings) reduced tree basal area of 18-yr old stands by approximately 20%. Ares and Brauer (2005) observed a small decrease in the diameter at breast height (DBH) for 19 yr-old loblolly pine trees grown in 4-row configurations as compared to double- or single-row configurations. This suggests the need for earlier or more aggressive thinning and pruning of higher within-row density stands regardless of whether they are single or multiple row plantings. Most of the changes in DBH were due to decreased DBH of the trees in the internal rows of the 4-row configurations. Decreases in tree biomass and bole biomass were greater than that of changes in DBH. Reduced tree performance is not compensated for by increased forage yield of multiple rows compared to single rows (Sharrow, 1991). Therefore, single and double tree rows are the most common patterns used in silvopastures.

The forage crop benefits from low tree densities. Unfortunately, the resulting "open grown" trees develop large branches extending close to the ground. The vascular system that supports these branches appears as knots in boards cut from these low quality logs. It is best to prune lower limbs when they are still alive. When trees heal over the pruning wound, the knots associated with that former branch tend to be "tight knots" that will stay in the board. If canopies lift naturally by shading out lower branches that then die and partially decompose before being grown over, the resulting knots are loose and leave holes in boards cut from the tree. There is currently a premium price paid for "clear", knot-free logs. Such logs can be peeled for veneer or cut into high grade dimension lumber. Therefore, silvopasture trees are pruned to increase log quality, as well as to maintain forage production. The objective of pruning is to produce a log containing a small knotty core without reducing tree growth rate. As silvopasture trees grow, lower limbs are removed in a series of canopy "lifts". Each canopy lift removes no more than one-third to one-half of the total crown length while maintaining a live crown equal to one-third of tree height (Fletcher et al., 1992). Pruning is generally continued to a final height of about 11 m. This produces two clear logs per tree. Log quality and the proportion of total tree biomass in the bole was greater 5 yr after pruning with 19-yr old loblolly pines in central Arkansas (Ares and Brauer, 2005). However, less biomass was found in the stem and more in needles and branches in trees grown in silvopasture, even when pruned, compared to trees in an adjacent forest at a DBH of 25 to 26 cm. In the past, saw timber prices failed to recover pruning costs, but the high value of knot-free logs on the current world market makes pruning a good investment (Fight et al., 1995). Because pruning is expensive and the removed branches pose a disposal problem, pruning is often limited to the "crop trees" that will be carried on to the final harvest age. Trees to be removed earlier during commercial thinning may not have enough growing years to produce sufficient clear wood to recover the cost of pruning, so are not pruned.

Silvopastoral trees often grow faster than trees under conventional forest management on the same site (Gibson et al., 1994; Hughes et al., 1965; Sharrow, 1995). It is unclear how much of this increased growth can be attributed to management of competition between trees and ground vegetation and how much is the result of greater soil nitrogen status from nitrogen fixation by silvopasture legumes. Silvopastures are also often fertilized with nitrogen, potassium, phosphorus, or sulfur to promote herbage growth. Some of this fertilizer is probably used to support increased tree growth compared to unfertilized forests. Prescription grazing in the absence of fertilization has been reported to increase both diameter and height growth for a number of conifer species (Sharrow, 1993; Sharrow, 1994). Although few studies are able to separate enhanced nutrient availability from reduced competition for soil moisture between trees and understory plants in agroforests, it is reasonable to assume that both factors combine to affect tree growth under grazing. Approximately half of the increased diameter growth of Douglas-fir in western Oregon silvopastures, compared to forests, occurs in the rainy spring period and half in the dry summer-fall period (Sharrow, 1995). This suggests that both increased soil fertility (in spring), and controlled competition for moisture (in summer–fall) contributed equally to enhanced growth of agroforest trees.

Tree species are selected to provide specific production and service functions. Most silvopastoral research has focused on commercial indigenous conifer species grown for wood production. In the United States, these include loblolly, longleaf, and slash pine in the southeastern region, and Douglas-fir and ponderosa pine in the northwestern region. Selection of populations of local trees that exhibit particularly rapid growth, good form, and adaptation to specific site conditions are a relatively cheap and effective way of improving tree performance. Widespread plants such as Douglas-fir, ponderosa pine, and loblolly pine often have genetically distinct populations (ecotypes) that are adapted to local site conditions. Moving these plants to other sites risks poor performance. For example, ponderosa pine in Oregon occurs both in the arid high desert zones of eastern Oregon and in the humid hills of western Oregon. Past attempts to use seed from eastern Oregon for afforestation of hill lands in western Oregon have largely failed because these desert trees are susceptible to disease and insect attack. Local ponderosa pine populations are more resistant to these attacks and have proven to be excellent commercial trees for hill land sites. Because of their drought tolerance, they do well on sites that are either too thinned soiled or too wet for Douglas-fir. It is best if "mother trees" for seedlings be from local sites similar to where they will be used. Higher genetic-potential trees such as improved selections of local varieties or introduced new types of trees have many advantages for silvopastoral systems, including: shorter establishment period when trees may be damaged by big game and livestock; quicker harvest and return on investment; greater annual wood production increment; and increased income. However, fast growth must be sustained by rapid capture of site resources. Faster growing trees, logically, should be associated with increased demand on soil moisture and soil nutrients. This will make management of site resource partitioning between trees and forage plants in time and space more critical. Acceptance of new types of trees such as nonnative trees or commercial hybrids by potential users has been slow because of concerns about their site suitability and potential marketability. Sharrow and Fletcher (1996) reported that the KMX hybrid pine, which expresses the cold hardiness of knobcone pine (*Pinus attenuata* Lemm.) and the fast growth of Monterey pine (*Pinus radiata* D. Don), initially grew almost twice as fast as Douglas-fir in hill land silvopastures. Uncertainty about its ability to withstand the extremes of climate and the potential marketability of KMX logs has greatly limited KMX use. Experience since 1995 has suggested that in many cases, KMX has not grown faster than local ponderosa pine plantations on the same site and tends to produce a big limbed tree with poor log quality unless carefully pruned. So, caution about widespread use of unknown plants may be warranted.

Hardwoods are used in many nonindustrial silvopastoral systems. Research related to hardwood silvopastures practices was recently reviewed by Garrett et al. (2004). However total area of hardwood silvopastoral systems is small compared to that of conifers. Hardwoods often require longer rotations to reach economic size. Hardwoods tend to be more palatable than conifers to both livestock and to wild herbivores. This increases their risk of being damaged by livestock, but makes them valuable as a potential source of forage (Fig. 6–3). Honeylocust (*Gleditsia triacanthos* L.), for instance, produces large pods that can serve as a valuable source of livestock feed (Wilson, 1991), while black locust trees provide forage and are strong nitrogen-fixing plants. Snell (1998) combined green ash (*Fraxinus pennsylvanica* Marsh.), American sycamore (*Platanus occidentalis* L.), and various red oak species with cool-season legumes and grasses. He found that initial hardwood growth and development was compatible with cattle when grazing was limited to the tree crop's dormant growing season. Other potential silvopasture tree crops include black walnut (*Juglans nigra* L.), cottonwood (*Populus deltoides* Bartr.), hickory (*Carya* spp.), Persian walnut

Fig. 6–3. Black locust trees planted into grass–clover pasture to fix nitrogen, provide forage, and produce rot-resistant fence posts.

(*Juglans regia* L.), persimmon (*Diospyros virginiana* L.), yellow poplar (*Liriodendron tulipifera* L.), and pecan (*Carya illinoensis* Wangenh) (Bandolin and Fisher, 1991; Rule et al., 1994; Ares et al., 2006). Climate, terrain, soils, and social acceptance can influence crop tree selection, yet the primary crop tree criterion is financial. Therefore, the selected crop tree should yield high-value tree products, respond to management manipulation, and have an existing market infrastructure. In the Pacific Northwest, red alder may be just such a tree. Although it is often viewed as a weed and grows multi-stemmed in unmanaged stands, it has rapid growth, fixes nitrogen, and its growth form is very responsive to management. Either pruning or combining it with other trees in rows to provide side competition for light will produce straight stems that have a ready market with local furniture producers. Its rapid growth makes it a potentially attractive short rotation companion intermixed with longer rotation Douglas-fir in silvopastures.

Silvopastoral Regions

Silvopastures are intensively managed production systems. Their commercial viability is influenced by land ownership patterns, soil conditions, climatic factors, proximity to timber and livestock markets, and transportation infrastructure. Because high productivity is generally required to justify the complex management of silvopastoral systems, the main silvopasture land base is nonfederal, rural land with annual timber production capacity of over 6 m^3 ha^{-1} and a forage production potential of 15 animal unit months ha^{-1}. The continental United States has 563 million ha of nonfederal rural land with distribution percentages for cropland, rangeland, pasture land and forest land being 27, 30, 10, and 28%, respectively. The southern and northwestern regions of the United States, a total of 19 states (Table 6–2), contain 274.8 million ha of nonfederal rural land, while accounting for 56% of the total forest land and 68% of the total pasture land. In addition to an adequate land base, the two regions have mild, moist climates suited for commercial timber and livestock production. Their rich legacy of timber and livestock management practices make them an excellent choice for the development and use of silvopastures.

Table 6–2. Nonfederal land cover classification for southern and northwestern United States in 2003 (Lubowski et al., 2006).

State	Cropland	Pasture	Rangeland	Forest Land	Federal Land
			1000 ha		
			Southern region		
Alabama	1015	1376	0	8713	404
Arkansas	3043	2154	0	6074	1256
Florida	1163	1465	1092	5153	1531
Georgia	1680	1132	0	8860	860
Kentucky	2217	2083	0	4253	524
Louisiana	2200	910	115	5398	530
Mississippi	2014	1305	0	6781	726
Missouri	5535	4320	36	4958	777
North Carolina	2231	741	0	6555	1015
Oklahoma	3630	3423	5718	2982	465
South Carolina	958	442	0	4517	419
Tennessee	1922	1925	0	4840	527
Texas	10,345	6409	38,895	4295	1178
Virginia	1158	1176	0	5334	1071
			Northwestern region		
Idaho	2207	533	2598	1622	13,583
Oregon	1498	713	3796	5153	12,651
Washington	2628	437	2731	5142	4825
California	3832	481	7186	5626	18,874

Southern Pine Region—History

In the southern United States, fire played an indispensable role in the growth and development of the forest forage resource. Low intensity surface fires set by lightning are responsible for the open, grassy understory of longleaf pine forests (Franklin, 1997; Wright and Bailey, 1982). Native Americans managed these natural forage resources by burning to sustain forage growth and guide animal movement (MacCleery, 1992; Robbins and Wolf, 1994). European settlers introduced domesticated livestock, primarily cattle, into these fire-mediated ecosystems. Unlike the Native American spiritual sense of stewardship, early European forage utilization bordered on exploitation rather than sustainability. Fires set to "green up" the forest understory sometimes resulted in wild fire that destroyed the trees. Cattle were allowed to roam on an open-range basis, often grazing forest land not owned by the cattlemen (Healy, 1985). Uncontrolled livestock grazing created problems that included overgrazing, seedling trampling, and soil compaction. Rotational burning improved cattle performance, but livestock concentration on burned forest range adversely impacted soils and reduced pine seedling growth. During the 1930s, landowners began fencing forest rangeland, equating good forestry with grazing prevention (Healy, 1985). This legacy of exploitative forest land grazing still flavors discussions between foresters and livestock graziers today. Many forest managers are reluctant to support grazing because they have had bad experiences in the past, or have heard of such experiences from others.

Early range and forest scientists understood the importance of fire to southern pine woodland management. Many of the warm-season (C_4) grasses native to southern rangelands are quite coarse and stemmy when mature. Livestock and native herbivores such as deer tend to prefer grazing on recently burned areas because forage plants begin to grow there earlier in the spring and the new growth is not intermixed with coarse growth from past years. Prescribed burning proved useful in improving nutritional value and maintaining yields of native forages (Halls, 1957; Lewis and Hart, 1972). Light intensity ground fires may also benefit southern pines by reducing disease problems and slowing establishment of unwanted shrubs and hardwood trees (Wright and Bailey, 1982). However, too frequent use of fire often results in a decline in forage yield due to overgrazing (Halls, 1957). Frequent burning can also deplete site productivity because much of the nitrogen in vegetation and litter is lost during combustion (Sharrow and Wright, 1977). Duvall and Whitaker (1964) found that cows and calves gained weight throughout the grazing season on rotationally burned forest rangeland. Rotational burning at 3- to 4-yr intervals maintained nutritive content and palatability of native forages, removed pine litter, and suppressed competing brush. They concluded that rotational burning could be used to integrate range and timber management. However, proper burning interval used to maintain soil fertility will vary between sites, with more productive sites tolerating shorter intervals between fires (Sharrow and Wright, 1977).

Southern Pine Region—Current Silvopastoral Situation

The Southern Pine Region encompasses approximately 164 million ha across the southern and southeastern United States and includes all or a part of fourteen states. The region extends from Virginia in the East, to Kentucky in the North, to the southern portion of Missouri and eastern portions of Oklahoma and Texas in the West, and to Florida in the South. Land use data (NRCS, 1992) indicate a forested forage resource of approximately 102 million ha. The majority of the resource occurs in the southern yellow pine, oak–pine, and oak–hickory forest cover types, with improved pasture land and native pastures accounting for 25 million ha (Shiflet, 1980). Most of the arable land has been devoted to crop production. However, 37% of the land is currently devoted to cattle production (rangeland and pasture), while woodlands and forests occupy another 37% of the land. Much of the pasture and forest land is potentially suitable for silvopasture (Pearson, 1991), making this the largest block of potential agroforest land in North America. The region is still predominately rural and 81% of rural land is privately owned. Forest lands in this region are fairly productive; more than 80% are capable of producing over 3.3 m^3 of commercial wood $ha^{-1}yr^{-1}$ (Merwin, 1997). It has a long-standing tradition of low-intensity forestry and cattle grazing that provides a firm basis for silvopastoral land use on pastures and nonindustrial forest lands. Principal commercial tree species include slash pine, longleaf pine, and loblolly pine. However, many sites historically supported hardwood forests and mixed pine–hardwood stands.

Forest grazing is by far the most common form of livestock use in southern forests. This is usually a low-input, low-intensity management approach to land use. The use of planted and fertilized pasture with pine trees to form silvopastures is becoming more common throughout the region (Fig. 6–4). Bandolin and Fisher (1991) cataloged numerous southern agroforestry systems that produced at least two of the following outputs: saw timber, pulpwood, plywood, veneer, firewood, nuts, fruit, livestock, and human food. They concluded that pine–cattle grazing systems dominated southern agroforestry, with 40 million ha in the states of Alabama, Florida, Georgia, and Louisiana capable of supporting such systems. Southern land-use professionals and agroforestry producers listed a loblolly pine–grass–cattle mix as the most common silvopasture practice (Henderson and Maurer, 1993; Zinkhan, 1996). Cattle are by far the dominant livestock component (Zinkhan, 1996).

Under favorable climatic and soil conditions, a silvopasture is a biologically, environmentally, and economically attractive approach for optimizing timber and livestock production. When the degree and timing of livestock grazing are properly controlled, southern pine woodlands may be grazed without endangering trees (McKathen, 1980; Peebles, 1980). Pearson et al. (1990) reported little or no damage to 1-yr loblolly and slash pines when the forage was intensively grazed for a short duration. However, they observed high rates of mortality when the forage adjoining 1-yr old loblolly pine trees was continuously grazed. Clason and Oliver (1984) reported that coastal bermudagrass growing in a properly managed loblolly–shortleaf pine (*Pinus echinata* Mill.) forest can support a livestock grazing program while maintaining a high level of timber productivity. A silvopasture management system developed by sprigging coastal bermudagrass into a 30-yr old pine stand has supported 7 mo of grazing (April to October) for 3.7 cow-calf grazing units ha^{-1} and produced 2 m^3 ha^{-1} of saw timber annually for 16 yr. Longleaf and slash pine respond positively to well-managed grazing. In north Florida, Lewis (1984) found that grazed longleaf pine survival was 15% less than ungrazed pine, but the grazed pines were 50% taller. Grazing reduced the level of plant competition allowing full sunlight to reach the seedlings, thus enabling seedlings to break out of the grass stage much earlier. Mills (1998) reported on a silvopasture in Florida. Slash pine seedlings were planted in twin row strips, 1.2 m between trees and 2.4 m between rows, with a 12.2 m open space between the strips. After the trees were planted, Pensacola bahiagrass was seeded on the open strips, and the area cut twice for hay in the first growing season. Grazing was initiated when the trees were 3 yr old using 2.5 cow-calf grazing units ha^{-1}. The area was fertilized with broiler litter at 2 Mg ha^{-1} every 2 yr, over seeded annually with crimson clover (*Trifolium incarnatum* L.), and limed every 3 to 4 yr according to soil test recommendations. This silvopasture has maintained annual cow herd conception rates at 90%, and mean annual timber production at 3.4 m^{-3} ha^{-1}.

On the upper Coastal Plain of the southeastern United States, a silvopasture established in a 30-yr old pine stand continuously produced timber and livestock for 25 yr (Clason and Oliver, 1984). Forage management practices, combined with periodic timber harvest, maintained a level of annual productivity that provided 168 d of warm-season grazing for 2.5 grazing units ha^{-1}, while annually growing 2.5 m^3 ha^{-1} of saw timber. The long-term production continuity of this silvopasture suggests that silvopastures of varying tree ages can be merged and managed on a landscape basis. There is a strong tradition of forestry and livestock production in southern woodlands. A large, well-managed contiguous forest and silvopasture land base would create a diversified commercial marketing system, which could stimulate rural economic development.

Midwest Region—Native Pecan Practices

Silvopasture practices are common within the floodplains of the midwestern United States, including eastern Kansas and Oklahoma, and western Missouri. This practice is an integration of native pecan trees with grasses and beef cattle. Many of the current stands in production resulted from selective thinning of naturally generated forests in the years immediately after World War II. Currently, over 90% of the pecan production in this region is from native stands (Reid and Hunt, 2000). Future production will come progressively more from planted trees. The herbaceous understory prevents soil erosion. Grazing by cow-calf pairs typically begins in April when cool-season grass growth is vigorous and continues until forage is exhausted in late summer, about August. Understory forage composition is often a complex mixture of introduced and native grasses. Tall fescue [*Schedonorus phoenix* (Scop.) Holub] can be a dominant plant in such systems (Ares et al., 2006). Grazing not only provides income from beef sales, it reduces the need for mowing, plowing, or other forms of understory vegetation control. Reported forage yields range from 6400 kg dry matter ha^{-1} in southern Oklahoma (Mitchell and Wright, 1991) to 2000 kg dry matter ha^{-1} in a dry summer in southeast Kansas (Ares et al., 2006). Native pecan trees

Fig. 6–4. Recently pruned southern pine silvopasture planted in rows.

often exhibit an alternate year bearing pattern, with high nut yields 1 yr and lower nut yields in the following year. Ares et al. (2006) reported that annual nut yields for 50- to 80-yr old pecan trees were fairly predictable over a 20-yr period, averaging 360 kg ha^{-1} in an "off" year and 800 kg ha^{-1} in an "on" year. Despite a lack of change in nut yields, tree trunk diameter and stand basal area increased with time. This increase in tree size requires that 1 to 2 trees per ha^{-1} be removed every 5 to 7 yr to prevent excessive overlap of tree canopies. Currently, timber from removed trees is seldom marketed. A variety of markets for this timber are available, including low-value products such as fuel wood or hardwood pulpwood and high value products such as saw logs or veneer. The profitability of pecan silvopasture is largely determined by the income from nut sales. However, beef production provides more consistent income, thus reducing the magnitude of the effects of the alternate bearing pattern of nut production on annual income. The net present values of these silvopastures could be increased significantly by marketing wood from pruning and thinning trees to enhance nut production (Ares et al., 2006).

Northwestern Region—Overview of Mixed Conifer Forest

The Northwest temperate zone includes Oregon, Washington, Idaho, and Montana. Natural forests range from the closed-canopy, humid Douglas-fir–Hemlock [*Tsuga heterophylla* (Raf.) Sarg.] coastal forests west of the Cascade Mountain Range to the more open-canopied interior mixed-conifer forests, and semiarid ponderosa pine–lodgepole pine (*Pinus contorta* Dougl.) extending from the Cascades to the eastern edge of the Rocky Mountains. The two principal commercial timber trees of the region, Douglas-fir and ponderosa pine together occupy over 28 million ha (280,000 km^2) in the Pacific Northwestern and Rocky Mountain states. They are harvested for both solid wood and wood fiber products. Fuel wood is an important subsistence product, which is used by approximately 14% of households as a source of heat (US Census, 1990). Rangeland livestock production and forestry are major contributors to the largely natural resource-based economy of the region. Approximately 5% of all privately owned nonurban land is pasture, 35% is rangeland, and 38% is forest. Understandably, by far the most prevalent agroforestry systems in the region are silvopastoral. Over half of all land in the region is federally owned, mostly managed by the USDA Forest Service, USDI Bureau of Land Management, and to a lesser extent, USDI National Park Service. Private forest and rangelands are often intermingled with public lands. Rangeland grazing on private land is often coordinated with adjacent public lands through grazing permits or leases. Federal land management goals for multiple use and resource sustainability, including aesthetic as well as physical products, greatly impact management practices on private as well as public lands throughout the region.

Cattle are the predominant livestock with sheep being locally important, especially for use in herded bands for prescription grazing. In many areas, the distinction between range and forest land is confused by a considerable area of forested rangeland that is managed for multiple uses, including both livestock and tree production. Rangeland and pastures are frequently interspersed with forest. The rectangular land grants offered to settlers often included untillable portions that were commonly used for livestock forage, farm woodlots, or persisted as relatively unmanaged forests. Homestead livestock were commonly allowed to forage in adjacent unclaimed government forest lands. Privately owned hay meadows and rangelands are often integrated with publicly owned forests and rangelands to provide a year-round forage base for livestock. Currently, high prices being paid for timber are encouraging farmers and ranchers to reforest pastures and marginal croplands and to intensify management of current woodlands. Low social acceptability of herbicides favors use of nonchemical approaches to forest vegetation management, such as livestock grazing.

The most common types of agroforestry in the northwestern zone are:

- Integrated forest grazing in which trees are grown above native rangeland vegetation
- Silvicultural prescription grazing in which livestock are used to facilitate tree establishment and growth
- Silvopastures in which livestock production is combined with commercial timber trees growing in introduced pasture

Although research experience with all three types of silvopastoralism has been accumulating since the 1950s, adoption of agroforestry systems has been slow. Considerable potential for expansion of current silvopastoral technology to new users along with refinement of existing agroforestry approaches still exists. In general, farmers and ranchers have been quicker to embrace agroforestry than have foresters, suggesting that systems that maintain forage and livestock production may be more rapidly adopted than those that focus more tightly on timber production.

When closed-canopy forests are opened up by timber harvesting, wind throw, or fire, they are capable of producing substantial amounts of ground vegetation to support both native and domestic herbivores. These early seral plant communities are referred to as "transitional ranges" by graziers who grazed them until the tree canopies again began to exclude forage plants from the understory. Aggressive timber harvesting on both public forests and private commercial forests during the 1970s and 1980s produced a large inventory of early seral vegetation that competed with young tree regeneration for site resources. Silvicultural prescription grazing (Sharrow, 1994) was developed as a socially acceptable and cost-effective alternative to herbicides or mechanical plant control for releasing young trees from competing vegetation. Livestock grazing also had the benefit of improving the young timber stands as a food source for deer and elk (Rhodes and Sharrow, 1990). Most of these older clearcuts are now mid-seral plant communities whose understory vegetation is declining as tree canopies close. It was expected that as heavily harvested commercial forest lands were growing the next generation of timber, harvesting on public forests would increase in the 1990s to meet immediate wood needs. This increase did not occur. Public concern about harvesting on public lands has resulted in a dramatic reduction of timber harvesting on federal and state lands in the Pacific Northwest. This has had three dramatic effects on forest management. First, it reduced availability of wood and substantially increased the price of logs. Oregon, for instance, imported approximately 200 million dollars more wood products from Canada then it exported in 2005. Second, forest production shifted from the extensive federal National Forest holdings to the many smaller nonindustrial foresters and ranchers. And, third, "old growth" protection reduced the available supply of large old trees, prompting local lumber mills to retool for smaller, second-growth logs. There is a high demand for logs ranging in size from 25 to about 120 cm in diameter. Big logs produced by longer timber rotations now sell at a discount because few mills want them. All of these trends favor agroforestry to some extent.

The more open-canopied inland and semiarid forests east of the crest of the Sierra Nevada–Cascade Range often produce grazable amounts of forage even when trees are large. Periodic wildfire and fires set as a land management tool by indigenous people once consumed brush and killed conifer seedlings. This kept the forest open and park-like. Fire exclusion during the past century has allowed abundant tree reproduction, especially in the ponderosa pine and lodgepole pine zone. The resulting crowded, closed-canopy forests support little understory vegetation and the weakly growing trees are susceptible to attack by insects. There is great interest in bringing these forests back to their former open-canopied structure through thinning and burning. Prescription grazing to stimulate growth of grasses and to manage growth of shrubs is a cost-effective and socially acceptable way to manage this understory vegetation for livestock production, big game habitat, and other multiple uses. Restored open-canopied forests should present substantial opportunities for agroforestry in both interior pine, and mixed-conifer forests.

Northwest Region—Silvopastures

Silvopastures incorporating conifer trees with seeded grass–legume pastures are among the most intensively managed, and most productive silvopastoral systems in the northwestern zone (Fig. 6–5). Although occasionally encountered east of the Cascade Mountains, these systems are currently most common in the valleys and foothills of western Oregon and western Washington. Most of the over one million ha of hill land in the western Pacific Northwest is privately owned. Much of this land historically supported white oak (*Quercus garryana* Dougl.) woodlands and savannahs. Hill lands are seldom used as croplands because of their steep slopes and shallow soils. Cattle and sheep grazing is the primary agricultural use. Large tracts of oak woodland were converted to improved pastures during the 1950s through early 1970s by felling oaks, burning, then seeding with forage legumes and perennial grasses. The resulting pastures are able to support one cow or five sheep ha^{-1} without irrigation. Some of these lands are now being reforested as silvopastures. High current timber prices have dramatically increased landowner interest in planting conifers and justify a higher intensity of land management. Agroforestry presents opportunities to increase hill land productivity by producing both trees and livestock products, to increase the diversity of plants and animals present, and to improve cash flow by combining immediate income from grazing with later income from sale of trees (Sharrow and Fletcher, 1995).

The original inhabitants of western Oregon were active land managers who used fire as a

Fig. 6–5. Five year old Douglas-fir–subclover–sheep silvopasture in western Oregon.

closed-canopy oak woodland and traditional forest or pasture monocultures. They are often park-like in appearance and social acceptability may be higher than for traditional forest plantations or pastures.

Douglas-fir is the most common silvopasture timber tree in western Oregon and Washington, followed by ponderosa pine. Both trees are important commercial species native to the local area. Agroforests based on these components tend to be socially acceptable to local people, biologically feasible, and to have present the needed infrastructure to market and process its products. Douglas-fir and ponderosa pine are high-value products when mature, although plantations may require 50 to 70 yr to mature, and 30 yr or more before they produce significant income. Landowners wishing to plant trees into existing pastures or oak woodlands often lack the capital available to forest managers who have just sold a timber stand. Immediate income from livestock or hay is likely to be an important factor making agroforestry more widely acceptable than forestry, especially for lands that are currently occupied by pasture or noncommercial woodlands. Speeding up the timber crop cycle, the rotation, by either increasing the growth rate of native conifers or by using faster growing exotic trees is an attractive solution to problems of high initial investment followed by poor cash flow typical of timber rotations (Table 6–3). Fertilization with nitrogen, phosphorus, and sulfur is a common practice on improved pastures, but rarely done for timber plantations. Silvopasture trees should benefit from access to both biologically fixed nitrogen as well as fertilizer nutrients applied to silvopastures.

Cool-season legumes, primarily subclover or white clover, and grasses such as perennial ryegrass or orchardgrass are included as a forage crop. The extensive fibrous root system of pasture grasses makes them fierce competitors for soil moisture and nutrients in the upper soil layers. Herbaceous competition in established pastures is generally controlled during the initial 2 yr after tree planting by spraying a 1- to 2-m circle with herbicide around newly planted tree seedlings (Fletcher et al., 1992). In general, more vegetation control is needed to increase

tool to produce grassy meadows and to keep oak woodlands open and park-like. Fire suppression in the last 150 yr has supported a successional process by which hardwood trees have invaded previously open grasslands and formerly open hardwood forests have become closed-canopy forests. Conifers, primarily Douglas-fir, grand fir [*Abies grandis* (Dougl.) Lindl], and ponderosa pine, are now beginning to overtop the canopy of hardwoods in many areas. Apparently, many hill lands will support conifer forests, but trees may be difficult to establish and growth rates are relatively slow compared to other commercial forest sites in western Oregon. Silvopastures may be successfully established in existing oak stands by thinning oaks, then under planting conifer trees and grass–clover pasture (Hedrick and Keniston, 1966). Young conifer trees have been observed to grow as fast under an open oak canopy as they do in clearcut areas (Jaindl and Sharrow, 1988). Livestock grazing often increases growth of young conifers by consuming vegetation that would otherwise compete with trees for stored soil moisture during summer droughts (Carlson et al., 1994). Retaining some large oak trees when establishing a silvopasture is an attractive option because many hill lands are near urban centers and scattered trees can actually increase land values (Diamond et al., 1987). Land use on the urban fringe must be especially sensitive to environmental quality issues, including environmental contamination, destruction of native plant or animal habitat, and visual appeal. Silvopastures are biologically more diverse than seedling growth than to just ensure its survival. Competition between young established trees and pastures is controlled by grazing to remove the forage canopy before soil moisture becomes exhausted (Doescher et al., 1987). When this is done, agroforest trees generally display less summer moisture stress and greater diameter growth than do nearby ungrazed forest stands (Carlson et al., 1994). In a trial near Corvallis, Oregon, for example, Douglas-fir silvopasture trees grew 14% faster in diameter than did adjacent forest trees during their first 4 yr (Sharrow, 1995).

Northwest Region—Integrated Forest Grazing: Native Forage Systems

By far the largest portion of the Northwestern Zone lies in the mountains and valleys extending eastward from the Cascade Mountain range, across the Great Basin, to the eastern edge of the Rocky Mountains. Elevation and topography are major determinants of vegetation throughout the zone. Valley bottoms that receive water from higher elevation watersheds often support salt desert, wetlands, or subirrigated hay meadows, while semiarid grasslands or grass–shrub lands are common at drier low- to mid-elevation sites. Upper elevation, more mesic sites support conifer forests. Semiarid open-canopy forests dominated by ponderosa and lodgepole pines are gradually replaced by more humid closed-canopy, mixed-conifer and Douglas-fir forests with increasing elevation or on more mesic sites.

Livestock and timber production are primary economic enterprises throughout the zone. Grazing by large bands of open-herded sheep was once common in both the Great Basin and Rocky Mountains (Oliver et al., 1994). Herded sheep grazing was a major local industry before the 1930s, but has continually declined since then, initially because of federal leasing policy under the 1934 Taylor Grazing Act, which favored cattle ranchers, and more recently because of difficulty finding and retaining competent herders, and excessive sheep losses to coyotes and other local predators. Cattle are now by far the most common livestock on western rangelands. The relatively low biotic productivity of semiarid rangelands together with their highly seasonal forage production encourages large scale livestock operations in which several different vegetation zones are integrated to provide a year-round forage base. Forested rangelands are an important link in this chain, providing green forage and shade during the summer and fall period. In many ways, these systems mimic migratory patterns of big game animals, such as deer and elk, which follow seasonal changes of elevational vegetation zones to avoid unpleasant weather and to stay in green feed. Most interior forests and forested rangelands are managed under multiple-use principles in which forage, wildlife, recreation, timber, and other natural resource values are harmonized. Whether current multiple-use management is sufficiently aggressive in manipulating the interactions among components to classify it as agroforestry is a subject of debate. Examples of structurally integrated livestock–timber systems in which livestock, forage, and forest management are designed to facilitate each other are common in interior forests. Such systems clearly meet the systems perspective and purposefully managed interactions associated with agroforestry. Often, however, forested rangelands and grazed forests are primarily managed for either their forest or rangeland values. In this case, forest grazing would qualify as an agroforestry-like practice rather than as true agroforestry.

Fire was traditionally an important agent in western forests. Summer thunderstorms, some of which lack appreciable rainfall, are a natural ignition source. Indigenous people also set fires to favor food plants and game animals and to keep areas more open for travel (Robbins and Wolf, 1994). High intensity fires in closed-canopy forests killed entire tree stands, favoring a patchy landscape of even-aged tree stands. Insects such as pine beetles (*Dendroctonus* spp.) attacked trees in stands missed by fires (Hessburg et al., 1994). In some ways their biological thinning of the stands was equivalent to the action of fire in controlling tree overstocking. The more open, grassy understory of many semiarid ponderosa pine and lodgepole pine forests is believed to be the result of frequent, low-intensity ground fires that reduced brush and killed young conifer regeneration without damaging large

Table 6–3. Net cash flow per hectare and internal rate of return (IRR) of three alternative land uses for western Oregon oak woodlands.†

Land use	Cash income above expenses					
	Years 1–5	Years 6–10	Years 11–15	Years 16–20	Total	IRR
	US$					%
KMX only	−1112	316	5,450	19,770	23,900	19
Sheep only	740	740	740	740	2,970	29
KMX + sheep	−126	300	330	8,144	20,120	22

† Analysis is based on a 20-yr KMX hybrid pine rotation and 10% discount rate. Costs and incomes are best estimates based on current market conditions and the experiences of local commercial agroforesters. (Sharrow and Fletcher, 1995).

established trees (Wright and Bailey, 1982). The resulting forest contained scattered large trees with a vigorous understory of native grasses and shrubs. Extensive areas of open-canopied forest were historically managed primarily as forested rangeland. They were important sources of livestock forage and contributed substantially to local economies. In 1907, for instance, 80% of revenue from eastern Oregon National Forests was from grazing fees and only 20% from timber sales (Oliver et al., 1994).

Fire suppression began in the early 1900s, yet did not become widely successful until needed infrastructure and organization developed in the 1930s (Oliver et al., 1994). Since that time, many interior forest stands have become choked with tree reproduction that was formerly controlled by fire. Closure of the tree canopy greatly depleted the herbaceous and shrub layers, reducing habitat for insects, mammals, and other animals that depend on these layers for food and shelter. Competition between trees in overstocked stands not only reduces tree growth, it also increases tree susceptibility to insect and disease attack. The high density of foliage in multiple canopy strata within these new closed-canopy forests provides a concentrated food source together with a ladder for easy insect movement (Lehmkuhl et al., 1994). Outbreaks of insects such as pine beetles, tussock moth (*Orgyis pseudotsuga* McDunnough), and spruce budworm (*Choristoneura occidentalis* Freeman) are becoming common in interior forests. Increased thinning and a three- to five-fold increase in use of prescribed burning (Lehmkuhl et al., 1994) are being advocated to restore ecological balance within overstocked interior conifer forests. This offers considerable opportunities for agroforestry.

Increased area of open-canopied conifer forests in the interior west will increase forage production. Structurally, these native forests resemble silvopastures and should follow similar ecological principles. Stand-level investigations of tree–understory relationships on forested rangelands have shown a general reduction of forage production with increasing conifer tree basal area (Tapia et al., 1990) or canopy (Sibbald et al., 1994). Established trees and ground vegetation compete for both aboveground (light) and belowground (soil moisture and nutrients) site resources. Krueger (1981), however, noted that forest forage production generally does not correlate with conifer canopy cover until average tree canopy cover exceeds 35%. Presumably, herbaceous production under dense tree canopies is limited by light while that of younger or more open-canopied forest is reduced by competition with trees for other site resources. Several authors have suggested that competition between large conifers and ground vegetation in open-canopied forest is primarily for soil resources (Krueger, 1981; McCune, 1986; Riegel et al., 1992). Within the belowground factor, soil nutrients are likely the most important factor in spring, while soil moisture dominates plant interactions in dry periods such as during summer or droughts (Riegel et al., 1991; Sharrow, 1995).

Soil resource sharing between grass and tree components is manipulated through both silvicultural and livestock management. Thinning or selectively harvesting trees to increase forage production is sometimes done, yet the practice is not widespread because of its cost. Most thinning is done for silvicultural reasons. Grazing is often timed to consume forage when it is green and nutritious. Most moisture use by plants is through evapotranspiration from living leaves. Grazing removes leaf area. In addition, grazed plants often shed roots to maintain an efficient root–shoot ratio (Motazedian and Sharrow, 1987). Timely grazing can reduce moisture withdrawal by grasses and shrubs, leaving more moisture for trees (Doescher et al., 1987). This is the basis for silvicultural prescription grazing in western conifer forests. Selecting the right tree species, with a deep root system, can also help reduce competition for soil resources between trees and grasses. Recent silvicultural interest in multispecies and multiage timber stands may also offer opportunities for using forest stand structure to facilitate resource sharing between trees and understory plants.

Northwest Region—Silvicultural Prescription Grazing

Silvicultural prescription grazing refers to grazing whose timing and intensity is designed to accomplish specific silvicultural objectives. Cattle, sheep, or goats are sometimes grazed for site preparation on harvested areas before replanting with trees to reduce vegetation that might impede planting crews or compete with new trees. Using cattle or sheep grazing to "release" young trees that are already onsite from competing vegetation is more common. Specific recommendations and general principles for conifer release using cattle and sheep grazing have been reviewed by Sharrow (1993; 1994), and Doescher et al. (1987). Increased growth of young trees attributable to grazing has been reported for ponderosa pine, Douglas-fir, western white pine (*Pinus monticola* Dougl. Ex D. Don), western larch (*Larix* *occidentalis* Nutt.), and white spruce (*Picea glauca* Moench). However, reports of silvicultural grazing being ineffective in substantially increasing conifer growth are also common. Tree release by grazing is most likely to be successful when:

- Livestock grazing is tightly controlled
- Competing vegetation is reasonably palatable
- Competing vegetation does not regrow quickly after grazing
- Grazing occurs sufficiently early in the growing season that competing vegetation has not exhausted soil moisture
- Sufficient vigorous trees are present to benefit from release
- Released trees are not palatable to livestock

Increased tree growth of 5 to 10% can be achieved when proper timing, intensity, duration, and class and type of livestock are applied to young conifer forests where grazable understory grasses or shrubs are competing with trees.

The Future of Silvopastoral Systems

There is a long history of livestock grazing in North American forests. Grazing has evolved since European explorers and colonists introduced cattle, pigs, sheep, goats, and horses to North America. Early grazing was mostly unsupervised with livestock having free range access to forests and woodlands. This uncontrolled grazing often resulted in damage to forest regeneration and gave livestock grazing a bad reputation with forest and woodland managers. Carefully controlled grazing now provides a tool by which livestock foraging can be used to further forest as well as livestock production goals. Silvopastoral systems seek to link the service and production functions of livestock, understory forage plants, and trees into a mutually supportive system of planned interactions. These functions sustainably produce marketable production of timber, fuel wood, livestock, and hunting as well as amenity values and environmental services. Environmental services such as clean air and water, scenic beauty, biodiversity, and carbon sequestration are already supported to some extent through tax abatement programs and cost sharing for sustainable practices. As these service values become more apparent to the general public, their willingness to pay for them should also increase. This new source of income should encourage increased application of earth friendly production such as silvopastures.

Approximately one-fifth of all forestland in the United States is currently grazed by livestock. This presents a substantial opportunity to implement silvopastoral systems by increasing the management intensity applied to these lands. In addition, the relatively high value of wood fiber during the past decade is encouraging livestock owners to afforest pastures, forming silvopastures. Although the area converted to date has been modest, it is a steadily increasing practice, particularly in the southeastern and northwestern states. Pastures and woodlands often occur on lands that are marginal for agriculture. These "secondary lands" have been under considerable development pressure as population pushes out into the countryside seeking small farm and ranch residences. Silvopastures produce a socially acceptable mix of agricultural production, scenic beauty and diversity of habitat for wildlife. Silvopastoral systems in North America have traditionally been embraced most readily by ranchers and nonindustrial forest land owners rather than by large private commercial or public land managers. Extensive harvesting of private forest land and policy decisions limiting harvesting from public forests, have increased the importance of smaller, nonindustrial forests as providers of wood and increased the prices paid for their products. This favors silvopastoral systems.

Adoption of silvopasture practices is currently hindered by landowner concern about livestock damaging trees, economics of livestock and timber production, and the complexity of managing joint production systems. Based on experiences with poorly designed livestock access to forests, consulting foresters and other natural resource consultants often believed that grazing animals adversely affected forested ecosystems. Further research and technology transfer activities are needed to educate both land owners and consulting professionals that the financial risk and the risk to natural resources within a silvopasture can be quite small if such ecosystems are managed appropriately.

Agroforestry in general, and silvopastoral systems in particular, are compatible with traditional agricultural practices and are favored by current economic, philosophical, and demographic trends in North America. Although it is unlikely that they will experience explosive growth in the next decade, they have a bright future and will always find a place in modern agriculture.

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Study Questions

1. Why are silvopastoral systems the most common types of agroforestry in North America?

2. Define *silvopastoral systems*, *integrated forest grazing*, and *silvopasture*. How do these practices differ?

3. Why are forest plantation trees generally planted equally spaced in a grid pattern while agroforestry trees are planted in rows?

4. What are the three developmental stages that agroforests potentially go through from establishment to maturity? How does the management of each stage differ?

5. How do the ecological concepts of *biological amplitude* and *ecological amplitude* apply to selecting tree, forage, and livestock components of silvopastoral systems?

6. Resource sharing in time and space is a fundamental concept in agroforestry. Describe what resources are being "shared" in silvopastures and how agroforesters manage trees, livestock, and forage to facilitate this sharing.

7. What is *silvicultural prescription grazing*? What practices are used to see that livestock do not damage trees?

8. Based on surveys conducted in the United States in both the Pacific Northwest and the Southeast, why do landowners adopt silvopastoral practices? What reasons do forest landowners give for owning land?

9. Silvopasture forage in the Pacific Northwest consists mostly of cool-season (C_3) plants, while southeastern silvopastures have mostly warm-season (C_4) forages. Explain what effect this difference has on managing tree–forage competition for light.

10. What is soil compaction? Does livestock grazing in silvopastures contribute to soil compaction?

11. What economic and social reasons may explain why farmers and ranchers are more likely to adopt silvopastoral practices than are foresters?

12. Pruning trees is more commonly done in silvopastoral systems than it is in commercial forests. What specific goals do silvopastoralists seek to achieve by pruning trees? What specific guidelines are followed to see that trees are not damaged by pruning?

13. Carbon sequestration is a type of "environmental" service provided by silvopastures. Explain why silvopastures may accrete (sequester) more carbon than either pastures or forests growing separately on the same site.

14. The major commercial timber trees used in the United States in both Pacific Northwest and Southeast silvopastures are conifers. Identify the two most common silvopasture trees from each region. Why aren't hardwoods more commonly used in silvopastures in these regions?